ELSEVIER
Available online at www.sciencedirect.com
SciVerse ScienceDirect
Energy Procedia 37 (2013) 1480 – 1489
Energy Procedia

GHGT-11

# Flue Gas Concentrations and Efficiencies of a Coal-fired Oxyfuel Power Plant with Circulating Fluidised Bed Combustion

Matthias Weng[a],*, Claas Günther[a], Alfons Kather[a]

[a]*Hamburg University of Technology, Institute of Energy Systems, Denickestraße 15, D-21073 Hamburg, Germany*

**Abstract**

In contrast to an Oxyfuel process with pulverised coal (PC) firing, possible advantages of a circulating fluidised bed combustion (CFBC) are the in-furnace sulphur dioxide removal – no additional sulphur dioxide removal downstream the steam generator might be necessary – and the feasibility for concepts with a reduced flue gas recirculation. In [1] design conditions for the overall process of an Oxyfuel CFBC with highest flue gas recirculation up to 75 % are compared to concepts with less recycled flue gas. Compared to [1], this work is not focussed on design aspects of the steam generator but rather on the changing structure of auxiliary power demand of an integrated overall process caused by a reduced flue gas recirculation. At full load operation and under realistic boundary conditions achievable efficiencies of an Oxyfuel CFBC will be examined and compared to the PC-fired Oxyfuel process.



*Keywords*: CCS, Oxyfuel, flue gas recirculation, circulating fluidised bed, CFBC

## 1. Introduction

To secure the energy supply in the future, coal will continue to play an important role due to its large reserves. However, specific and absolute $CO_2$ emissions are among the highest when burning coal for power generation. Therefore, the capture of $CO_2$ from coal-fired power plants may contribute significantly in reducing global $CO_2$ emissions. The Oxyfuel process is one of the approaches under examination for carbon capture and storage (CCS) to reduce the amount of emitted $CO_2$. It is based on the approved steam

* Corresponding author. Tel.: +49-40-42878-3421; fax: +49-40-42878-2841.
*E-mail address:* matthias.weng@tuhh.de.


doi:10.1016/j.egypro.2013.06.023

power process and therefore will profit from a high reliability and efficiency. The design of the process intends the combustion of coal in an atmosphere of $O_2$, provided by an air separation unit (ASU), and recycled flue gas, resulting in a flue gas with high $CO_2$ concentration.

The amount of recycled flue gas in the Oxyfuel process depends essentially on the deployed firing system. For most large new build, high efficiency power plants PC firing is used as firing system. Both the fuel properties as well as limitations of steam and metal temperatures of the various heat exchanger sections in the steam generator require a moderation of the temperature during combustion. In order to control this issue a large quantity of flue gas has to be recycled back to the furnace to achieve an acceptable temperature level throughout the steam generator. However, an efficiency drop for the Oxyfuel process is caused by a significant auxiliary power demand of the fans for the recirculation of flue gas beside the ASU and the purification, liquefaction and compression of the $CO_2$ in a gas processing unit (GPU).

Approximately two thirds of the entire flue gas stream has to be recycled for a hard-coal-fired Oxyfuel process with PC firing [2]. A possibility to reduce this amount is to adopt another heat sink in the system. As this opportunity does not exist for PC-fired units, the application of a circulating fluidised bed combustor seems applicable. Huge amounts of solid particles are circulated in such a firing system. This material can be used as a heat sink in the combustion chamber (CC) and simultaneously as a heat source in external heat exchangers (EHEs) thus keeping the combustor temperature at a constant allowable level. The temperature of the combustion can be maintained independent of the chosen amount of recycled flue gas when firing with $O_2$ by simply cooling a greater portion of the solids in the recirculation loop.

Similarly it is possible in an $O_2$-fired CFBC system to reach a distribution of heat quantities within the steam generator that are very similar to air firing using the proper amount of recycled flue gas. This scenario would represent the most conservative $O_2$-fired condition with highest flue gas recirculation of 70 – 75%. In such a scenario the size and costs of the CC, the cyclones, the EHEs, the convective heat exchangers (CHE) and other components of the steam generator would also be approximately identical to the air-fired case. The mentioned conservative case will be compared in this work to design conditions with less recycled flue gas and changing requirements for the overall CFBC Oxyfuel process. In contrast to [1], this work is not focussed on design aspects of the steam generator but rather on the consequences on $CO_2$ concentrations and on the structure of the auxiliary power demand of the overall process caused by a reduced flue gas recirculation which will be examined and summarised at full load operation. Furthermore achievable overall efficiencies under Oxyfuel conditions of a CFBC process will be compared to the PC-fired process.

## 2. The Oxyfuel process with circulating fluidised bed combustion

A simplified process scheme for the Oxyfuel CFBC considered in this work is shown in Figure 1. The Oxyfuel process with CFBC differs from the PC-fired process in particular by the use of entrained hot particles as an additional heat carrier beside the flue gas. Most of the entrained particles are separated in the cyclones. The separated solids enter a loop-seal, while the flue gas enters the CHE. After the loop-seal a controlled cooling down of the particles can be realised outside the CC. Therefore the particles can be forwarded directly back to the CC or for controlled cooling of the particles to EHEs. Accordingly the examined Oxyfuel process with CFBC is based on a system with EHEs. Fuel, additional inert material and sorbent (e.g. $CaCO_3$) are mixed with the entrained particles in the return leg to the CC.

Beside the fluidisation of loop-seals, CC and also EHEs have a certain fluidisation demand. Due to the large difference between the pressure loss in the EHEs and the CC ($\Delta p_{EHE} \approx 3.5 \cdot \Delta p_{CC}$) both components are fluidised by flue gas of different recycles. The first branch point for flue gas recirculation is directly downstream the electrostatic precipitator (ESP) at a temperature of approx. 245 °C. This flue gas is mixed with $O_2$ supplied by the ASU and is fed into the CC via nozzle floor or as a secondary oxidant above the refractory lining. The remaining part of the flue gas is further cooled down to approx. 100 °C. This cooler transfers heat to a condensate bypass economiser. The availability of state-of-the-art flue gas compressors to realise a pressure increase of about 400 mbar, as required for EHE fluidising, combined with high flue gas temperatures in the range of 150 – 350 °C is restricted. Therefore the temperature level on the suction-side of the compressor for the fluidisation of the EHEs is lowered to ensure an unrestricted operation of such a compressor. At CHE outlet there is still heat on a high temperature level in the flue gas to reheat the recycled flue gas for fluidising the EHEs. In addition a parallel cooler transfers heat to a feedwater bypass economiser.

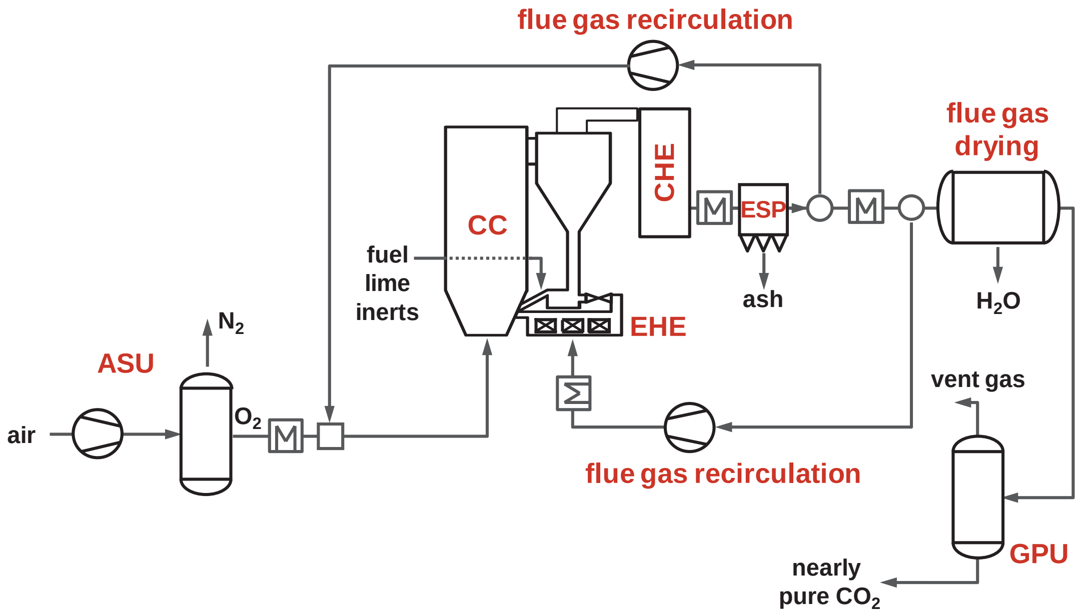


Figure 1: Simplified process scheme of an Oxyfuel circulating fluidised bed combustion (CFBC) process

The integrated overall process of the Oxyfuel power plant with CFBC bases on a greenfield power plant concerning data of available high end CFBC steam generators [3]. A once-through supercritical steam generator with gross power output of 460 $MW_{el}$ is assumed. Design fuel for the steam generator is South African hard coal with a lower heating value of 25.1 MJ/kg. The preheating train consists of three condensate preheaters, one feedwater tank and three feedwater preheaters. The condenser pressure is 45 mbar. State-of-the-art isentropic efficiencies are chosen for HP, IP and LP turbines, while in the last stages of the LP turbine influences by droplets of wet steam are considered. To receive comparable conditions for combustion and by these reliable results for a comparison of concepts with different amounts of recycled flue gas, the local $O_2$ ratio has to be kept at a constant level. The operating pressure of CC, loop-seals and EHEs is higher than ambient pressure. For this reason air ingress is neglected for these components. The construction of the CHE path should be gas-tight, so no air ingress is considered here as well. The only air ingress assumed for CFBC is set at the ESP. Depending on manufacturer's data low air ingress can be guaranteed for such an ESP. In this case air ingress of about 0.5 %, related to the volume flow under standard conditions, is considered at the ESP representing air ingress for the whole flue gas train operated below ambient pressure. In contrast to PC-fired steam generators, where an additional air ingress has to be considered for the gap between burner and furnace or for burner cooling [4], the lower potential for air ingress seems to be an advantage for an Oxyfuel process with CFBC. All chosen assumptions are in agreement with data from manufacturing and supplying companies. The most important assumptions for the considered Oxyfuel process with CFBC are summarised in Table 1.

The influence of a different atmosphere in the CC under Oxyfuel conditions affects the in-situ desulphurisation. It is not sure whether a direct sulphatisation or an indirect sulphatisation of the added limestone will occur under Oxyfuel conditions. Currently many researchers are trying to evaluate the influence of Oxyfuel conditions on the sulphatisation mechanisms with varying results [5], [6]. In this work a rather more optimistic approach is chosen. It is assumed that no secondary measures have to be realised for CFBC due to the assumption of a sufficient sulphur dioxide removal in the CC.

Table 1: Selected assumptions for the considered Oxyfuel process with CFBC

| | |
|---|---|
| Gross power output | 460 $MW_{el}$ |
| South African hard coal (LHV) | 25.1 MJ/kg |
| Live steam temperature | 560 °C |
| Live steam pressure | 275 bar |
| Reheat temperature | 580 °C |
| Condenser pressure | 45 mbar |
| $O_2$ ratio (local) | 1.15 |
| FBC outlet temperature | 880 °C |
| Air ingress | 0.5 % |
| $O_2$ purity | 95 vol.-% |
| ASU specific demand | 236 $kWh/t_{O2,pure}$ |
| $CO_2$ capture rate | 90 % |

In general the supply of $O_2$ causes approx. 50 % of the net efficiency loss of a non-integrated Oxyfuel power plant if a conventional cryogenic ASU design for high $O_2$ purity of more than 99.5 vol.-% is selected. Lower $O_2$ purities of around 95 to 97 vol.-% are the most effective option to reduce the energy demand of a cryogenic ASU [7]. The efficiency loss caused by $O_2$ production is reduced much more than the increase of the GPU energy demand due to larger content of impurities in the flue gas. Nearly the complete power demand of the main air compressor in the ASU is transformed into heat. The efficiency increase caused by using this heat source depends mainly on its temperature level. Isothermal compression using several intercoolers reaches temperatures of approx. 90 °C. An adiabatic compression without intercoolers can reach 190 - 220 °C depending on the pressure ratio and the inlet temperature of air. Regarding the heat sink, $O_2$ preheating is the most efficient option. However, the potential for efficiency improvement is limited, as significantly more heat is available than can be transferred to the $O_2$ stream. In this work a configuration with adiabatic compression without intercoolers is used to provide $O_2$ by a cryogenic ASU (double column process with additional reboiler). The supplied $O_2$ at the outlet of the ASU has a purity of 95 vol.-% while the specific energy demand is 236 kWh/$t_{O2,pure}$ (no benefits for heat integration included). The demand of heat required for thermal regeneration of the molecular sieves in the ASU will be supplied by extracted steam from the cross-connection between IP and LP turbine. The temperature level of about 190 °C of the compressed air is used for preheating the $O_2$ stream inside the ASU up to about 180 °C. A second parallel aftercooler transfers the residual heat to a condensate bypass economiser. Although the specific energy demand of $O_2$ production increases as the adiabatic compression shows a higher power demand, the overall net efficiency increases due to the use of heat integration and the higher temperature level. The $O_2$ is further preheated to approx. 315 °C by using the flue gas leaving the CHE.

Beside the ASU the GPU is another component which leads to a significant net efficiency loss. In this work the GPU is regarded as isobaric $CO_2$ condensation with two-stage external cooling-system as shown in Figure 3 (b). After removing rest water out of the flue gas, subsequently the flue gas stream gets separated into a $CO_2$-rich and a $CO_2$-lean stream inside the GPU. The $CO_2$-lean stream leaves the process as vent gas of the GPU while the remaining pressure is used to generate electricity in the vent gas turbine. The liquefied $CO_2$-rich stream can be compressed to the final pressure of 110 bar by using a $CO_2$ pump. For these examinations the $CO_2$ capture rate is held constant at 90 % while the achieved $CO_2$ purity at GPU outlet depends essentially on the $CO_2$ concentration at the inlet of the GPU. The heat demand required for thermal regeneration in the GPU will be supplied by extracted steam like for the ASU. Heat to be dissipated is transferred to the cooling system of the power plant.

A reduced flue gas recirculation leads to significant changes in the design and the operation of an Oxyfuel process with CFBC. In terms of design, parts of transferred heat in CHE, CC and EHEs differ considerably with a variation of the flue gas recirculation and a constant CC outlet and EHEs outlet temperature. In general a reduced flue gas recirculation leads to a decreasing flue gas mass flow in the CHE. Less heat is transferred in the CHE to the water-steam-side. Furthermore a decreasing flue gas recirculation causes a reduced CC cross-sectional area for a constant flue gas velocity. Available CC wall surfaces and additional platen superheaters and wing-walls in the CC are smaller so that the heat transferred in the CC decreases as well. Because both CC and CHE decrease in the amount of transferred heat, more heat has to be transferred to the water-steam-side inside the EHEs. For detailed informations about the assumptions for the modelling and the results about the influence of a reduced flue gas recycle on the design of the steam generator, the reader's attention is drawn to [1].

## 3. Process Modelling

The integrated overall process of the Oxyfuel power plant with CFBC is modelled using the commercial software EBSILON®*Professional*. For the modelling of the ASU specific characteristics are assumed for the energy demand, the heat and cooling duty representing a double column process with additional reboiler and adiabatic compression. In addition Aspen®Plus is used to simulate the purification, liquefaction and compression of the $CO_2$ in the GPU to take account of changing flue gas compositions and mass flows caused by a reduced flue gas recirculation. Both programmes are linked with a programmable dynamic link library (ProgDLL). A simplified scheme of this connection and the transfer of input parameters are shown in Figure 2. The linking via ProgDLL allows the simultaneous execution of both software applications.

In the first iterations the operation of the GPU is not taken into account. After 100 iterations the resulting composition and mass flow of the flue gas are used as input parameters for the GPU model in Aspen®Plus. The results of GPU calculation – power requirements, cooling and steam demand and the achievable $CO_2$ purity – return as input parameters to the overall process model. This loop will be executed every 100 iterations till the given accuracy is reached. The mentioned procedure facilitates an evaluation of the overall process with varying flue gas recirculation to consider all changing requirements and their influence on the overall efficiency and the achievable $CO_2$ purity of the $CO_2$-rich stream.

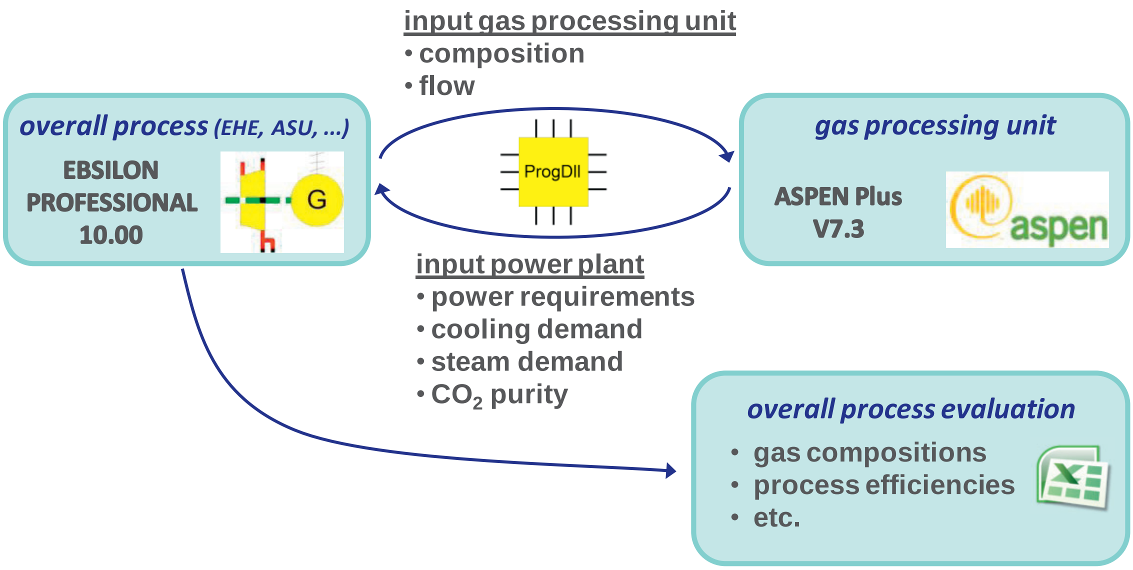


Figure 2: Simplified scheme of modelling procedure for the overall process evaluation

The description of solid entrainment or particle heat transfer is not possible with standard components using EBSILON®*Professional*. Therefore *Kernelscripts* can be programmed to describe all key components like CC, EHEs or loop-seals via characteristical mathematical approaches representing large-scale CFBC power plants. A more detailed description of CC, EHEs and loop-seals modelling is given in [1].

## 4. Results

For an Oxyfuel concept with reduced flue gas recirculation the EHEs become more important in comparison to the air case. In terms of transferred heat quantities the conventional air case is similar to an Oxyfuel concept with highest flue gas recirculation of approx. 70 – 75 %. With decreasing flue gas recirculation the cross-sectional area of CC and CHE are continuously becoming smaller. Less heat can be transferred in CC and CHE which has to be compensated by an increasing amount of heat transferred in the EHEs. For this reason, the number and size of EHEs increase as well as its fluidising gas demand. If the EHEs and loop-seals are fluidised with recycled flue gas there will be always a certain fluidising gas demand so the flue gas recirculation cannot be reduced in any order. A theoretical design limit at approx. 38 % flue gas recirculation occurs which is highlighted in the following diagrams. This value represents the absolute theoretical design limit and the minimal flue gas recirculation for the selected assumptions. At this theoretical design limit the whole recycled flue gas is used for the fluidisation of the EHEs. The CC is solely fluidised with $O_2$ supplied by the ASU. Therefore the $O_2$ concentration in the oxidant which is fed into the CC via nozzle floor or as secondary oxidant would be the same $O_2$ concentration like in the fresh $O_2$ stream of the ASU (95 vol.-%). The dilution with $CO_2$ of the recycled flue gas is missing. The presence of such high concentrations of $O_2$ at the CC inlet might lead to problems during combustion. Sintering and agglomeration of particles can arise caused by excessively high temperatures in the dense bed of the CC. In the worst case a shutdown of the steam generator is required.

In addition to this theoretical design limit, another more practical design limit can be defined. Different practical problems can occur restricting the technical feasibility of an Oxyfuel process with reduced flue gas recirculation. Problems to realise a concept with lowest flue gas recirculation might be an insufficient velocity above the nozzle floor in the CC or inadequate space around the CC for the installation of EHEs while the solid flow rate in a single EHE is limited. The available amount of particles for the heat transfer in the EHEs is less than the quantity which is needed to transfer the required amount of heat in the EHEs. The minimal flue gas recirculation for the simulated process set-up and by this the practical design limit is at about 57 %, also highlighted in the following diagrams. Under the given assumptions, the minimal flue gas recirculation cannot be lower than this limit not to compromise the feasibility of the process. However, it has to be taken into consideration that the $O_2$ concentration for the oxidant entering the nozzle floor of the CC is approximately 60 vol.-% (dry) and by this about three times higher compared to the conventional air-fired process. Problems might occur during operation of the power plant with a reduced flue gas recirculation, which still have to be further analysed via measurements. For instance the restricted oxidant staging and its influence on NOx emissions under Oxyfuel conditions with reduced flue gas recirculation are neglected in these calculations.

In Figure 3 (a) the volumetric $CO_2$ concentration at GPU inlet and outlet are shown as a function of a varying flue gas recirculation. Beside general changes in steam generator design a decreasing flue gas recirculation leads to a higher flue gas mass flow at the inlet of the GPU due to a decreasing $CO_2$ concentration in the flue gas. In particular impurities like the residual $O_2$ in the flue gas are increasing if less flue gas is recycled. Accordingly the design of the GPU has to be adapted to the specific flue gas recycle conditions. The lower the $CO_2$ concentration at GPU inlet the lower is also the achievable $CO_2$ concentration at the outlet of the GPU. For the practical design limit the $CO_2$ concentration at GPU outlet is 97.9 vol.-% (dry) and about 0.3 vol.-% lower compared to a flue gas recirculation of 75 %.

Influenced by the changing $CO_2$ concentrations, the specific energy demand for the GPU increases just slightly from 112.9 $kWh_{el}/t_{CO2,pure}$ for 75 % to 113.3 $kWh_{el}/t_{CO2,pure}$ for 57 % flue gas recirculation. This increase is also obvious for the absolute electrical power demand of the GPU, see Figure 4 (a).

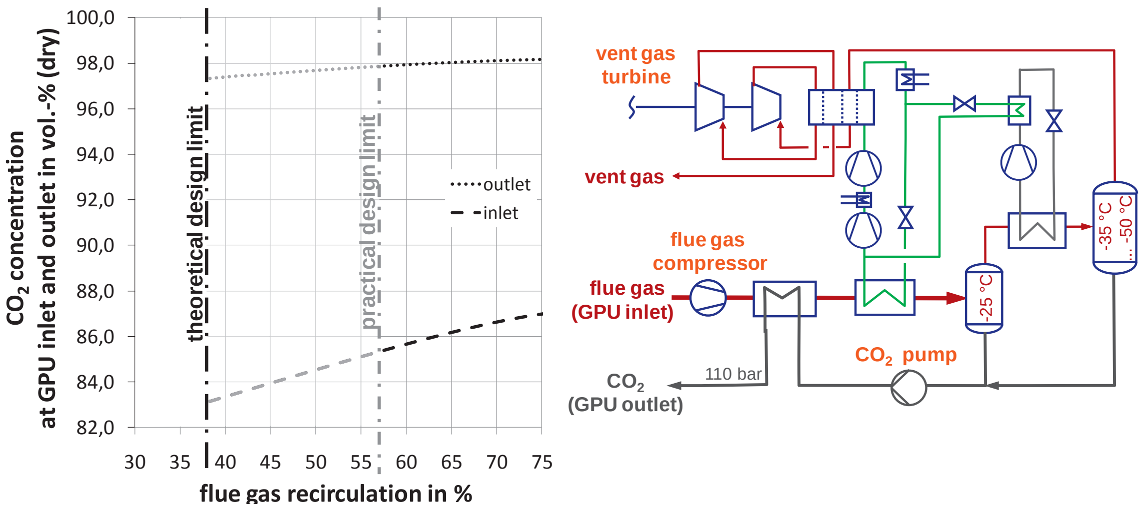


Figure 3: (a) Volumetric $CO_2$ concentrations at GPU inlet and outlet for a variation of the flue gas recirculation of an Oxyfuel CFBC; (b) Simplified GPU process scheme of the isobaric $CO_2$ condensation with two-stage external cooling-system (refrigerant: first loop $NH_3$ / second loop $CO_2$)

Beside varying conditions for the GPU a reduction of recycled flue gas leads to changing conditions of operation for the ASU. More $O_2$ has to be supplied by the ASU if less $O_2$ is provided by the recycled flue gas. The power demand for the ASU will increase from 65.7 $MW_{el}$ for a flue gas recirculation of 75 % to approx. 67.7 $MW_{el}$ for the practical design limit. The power demand for the fluidisation of the EHEs and loop-seals will increase from about 2.8 MW for 75 % to 3.5 MW for 57 % flue gas recirculation due to an increasing fluidising gas demand. In the opposite direction the power demand for CC fluidisation is changing. About 7 $MW_{el}$ can be saved for the practical design limit compared to a high flue gas recirculation of 75 %. This is the main advantage in auxiliary power demand of an Oxyfuel CFBC concept with reduced flue gas recirculation and leads to net efficiency gain of about 0.7 %-points for the practical design limit compared to 75 % flue gas recirculation, see Figure 4 (b). Therefore a net efficiency of 34.77 % occurs for the Oxyfuel CFBC concept at the practical design limit. Beside an increasing net efficiency there is also a slight increase of 0.1 %-points in gross efficiency. On the one hand, the less flue gas is recycled the less heat can be transferred in the condensate and feedwater bypass economiser to the water-steam-side. On the other hand, the less heat is transferred in these bypass economisers the higher is the efficiency of the Clausius Rankine process for which reason a slight increase in gross efficiency occurs.

The net efficiency for the conventional air-fired CFBC process is calculated to 43.6 %. In comparison to the Oxyfuel concept at the practical design limit a net efficiency loss of about 8.8 %-points will persist. The efficiency loss could be further reduced slightly by using optimised cryogenic ASU processes (multicolumn processes) and a higher level of integration. The integration of such a multicolumn process into an Oxyfuel power plant becomes more difficult if part load behaviour plays an essential role.

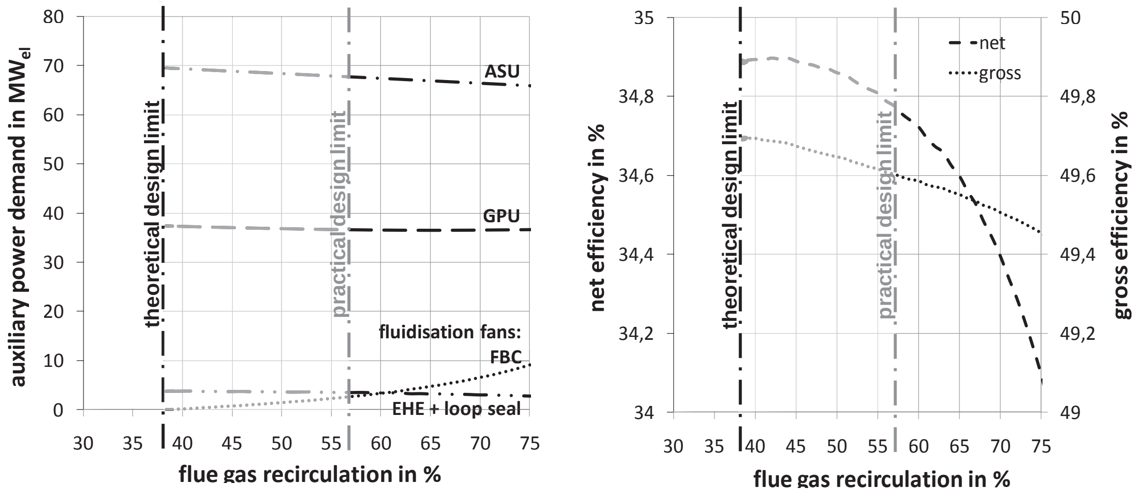


Figure 4: (a) Auxiliary power demand of selected components for a variation of the flue gas recirculation of an Oxyfuel CFBC; (b) Net and gross efficiencies of the overall process

For the PC-fired Oxyfuel process with same steam parameters the net efficiency of the overall process is in between 34.7 – 35.2 % which depends on the chosen branch point for flue gas recirculation. Compared to the PC process no improvement of net efficiency can be achieved with the use of a CFBC, especially if an additional secondary flue gas treatment for SOx removal is necessary. In particular the much higher pressure losses in the steam generator compared to the PC process lead to a much higher energy demand for the blowers to recycle flue gas.

## 5. Summary and outlook

A limited reduction of the flue gas recirculation for an Oxyfuel process with CFBC seems technical feasible and leads to a slight increase in net efficiency. However an efficiency loss of about 8 %-points will persist compared to the conventional air-fired process with CFBC, even if the whole potential for process optimisation and integration is used. To increase the efficiency further higher live and reheat steam parameters with more than 600 °C are suitable. As there is no experience with such high steam parameters in a CFBC steam generator, the PC process has a clear advantage to achieve highest efficiencies even under Oxyfuel conditions due to the greater experience with highest steam parameters.

Beside an evaluation of process efficiencies an Oxyfuel process with CFBC and reduced flue gas recirculation might be an alternative to the PC-fired process in terms of economics. The less flue gas is recycled to the CC the smaller the cross-section and the costs for the CC will get. On the other hand costs for EHEs will increase. Therefore an economic evaluation of Oxyfuel concepts with CFBC and reduced flue gas recirculation is also in the scope of this project.

## Acknowledgements

This work is performed under a joint research project with the Institute of Combustion and Power Plant Technology of the University of Stuttgart, the Institute of Power Engineering of Dresden University of Technology and the Institute of Energy Systems of Hamburg University of Technology. Financial support is provided by the German Federal Ministry of Economics and Technology (FKZ 0327872A / ADECOS ZWSF) with additional funding from EnBW Kraftwerke AG, E.ON Energie AG, Linde AG, RWE Power AG and Vattenfall Europe Generation AG. Moreover technical support is delivered by Doosan Lentjes.

## References

[1] Günther, C.; Weng, M.; Kather, A. – Restrictions and Limitations for the Design of a Steam Generator for a Coal-fired Oxyfuel Power Plant with Circulating Fluidised Bed Combustion. *11th International Conference on Greenhouse Gas Technologies, Kyoto, Japan,* 18th – 22nd November 2012.

[2] Kather, A.; Scheffknecht, G. – The oxycoal process with cryogenic oxygen supply. *Naturwissenschaften*, DOI 10.1007/s00114-009-0557-2, 2009.

[3] Jäntti, T.; Parkkonen, R. – Lagisza 460 $MW_e$ Supercritical CFB - Experience During First Year After Start of Commercial Operation, *Russia Power*, March 2010.

[4] Kownatzki, S.; Kather, A.; Günther, C. – $CO_2$ Purity in Coal Fired Oxyfuel Processes. *2nd IEA GHG Oxyfuel Combustion Conference, Yeppoon, Australia*, September 2011.

[5] Tan, Y. et. al. – Operation Experiences and Results with a Pilot-scale Oxy-fuel Circulating Fluidized Bed. *2nd IEA GHG Oxyfuel Combustion Conference, Yeppoon, Australia,* September 2011.

[6] Tourunen, A. et. al. – Small pilot scale CFB experiments under air- and oxygen-firing conditions. *2nd IEA GHG Oxyfuel Combustion Conference, Yeppoon, Australia*, September 2011.

[7] Klostermann, M.; Kather, A. – Efficicency increase of oxyfuel processes by integration and optimization. *1st IEA GHG Oxyfuel Combustion Conference, Cottbus, Germany*, September 2009.